I Laboratori Nazionali di Legnaro
LNL

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Dipartimento
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e Astronomia
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Searching Axions through coupling with spin: the QUAX experiment

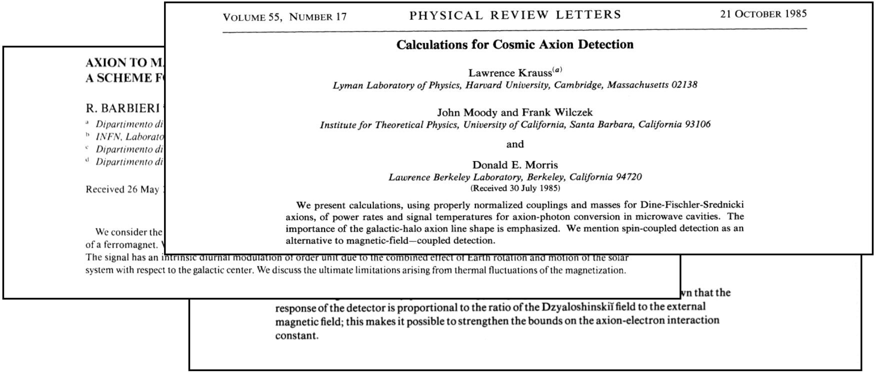
Nicolò Crescini
Università di Padova, Laboratori Nazionali di Legnaro
for the QUAX collaboration

January 12th 2017

Introduction

1. Introduction
2. Axion-Spin interaction
   Axionic field acting on magnetized materials: the effective magnetic field.
3. Dark matter properties
   Experimental hypothesis and features of the axionic "wind".
4. Cavity detection and hybridization
   Combining the ESR with the resonances of a microwave cavity.
5. First experimental results
   Cavity-sample coupling and noise measurement.
6. Limitation and possibilities
   SQL and linear amplification vs. single microwave photon counter.
7. Conclusions

Theoretical suggestions



VOLUME 55, NUMBER 17 PHYSICAL REVIEW LETTERS 21 OCTOBER 1985

Calculations for Cosmic Axion Detection

Lawrence Krauss[(a)]
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

John Moody and Frank Wilczek
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106

and

Donald E. Morris
Lawrence Berkeley Laboratory, Berkeley, California 94720
(Received 30 July 1985)

We present calculations, using properly normalized couplings and masses for Dine-Fischler-Srednicki axions, of power rates and signal temperatures for axion-photon conversion in microwave cavities. The importance of the galactic-halo axion line shape is emphasized. We mention spin-coupled detection as an alternative to magnetic-field—coupled detection.

AXION TO M
A SCHEME F

R. BARBIERI
[a] *Dipartimento di*
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[c] *Dipartimento di*
[d] *Dipartimento di*

Received 26 May

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The signal has an intrinsic diurnal modulation of order unit due to the combined effect of Earth rotation and motion of the solar system with respect to the galactic center. We discuss the ultimate limitations arising from thermal fluctuations of the magnetization.

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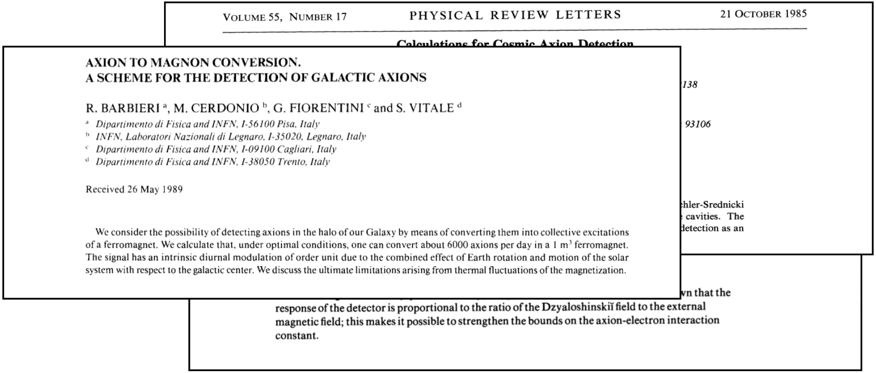
First paper: 1985 by L.M. Krauss, J. Moody, F. Wilczek, D.E. Morris.

Theoretical suggestions



VOLUME 55, NUMBER 17 PHYSICAL REVIEW LETTERS 21 OCTOBER 1985

Calculations for Cosmic Axion Detection

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detection as an

AXION TO MAGNON CONVERSION.
A SCHEME FOR THE DETECTION OF GALACTIC AXIONS

R. BARBIERI [a], M. CERDONIO [b], G. FIORENTINI [c] and S. VITALE [d]
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Received 26 May 1989

We consider the possibility of detecting axions in the halo of our Galaxy by means of converting them into collective excitations of a ferromagnet. We calculate that, under optimal conditions, one can convert about 6000 axions per day in a 1 m^3 ferromagnet. The signal has an intrinsic diurnal modulation of order unit due to the combined effect of Earth rotation and motion of the solar system with respect to the galactic center. We discuss the ultimate limitations arising from thermal fluctuations of the magnetization.

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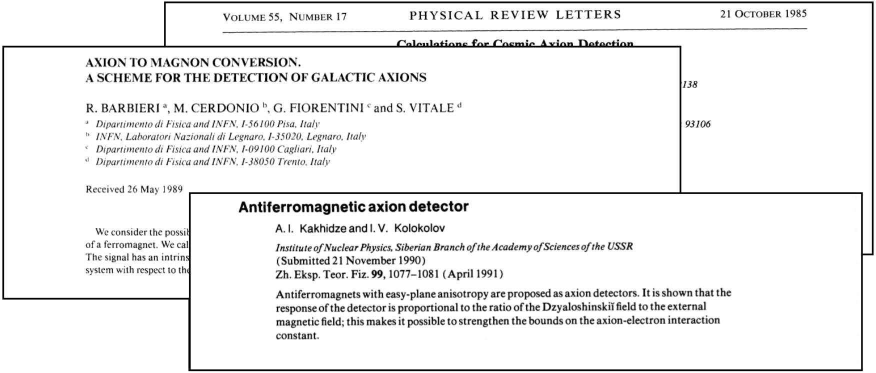
Second paper: 1986 by R. Barbieri, M. Cerdonio, G. Fiorentini, S. Vitale.

Theoretical suggestions



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A SCHEME FOR THE DETECTION OF GALACTIC AXIONS

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Antiferromagnetic axion detector

A. I. Kakhidze and I. V. Kolokolov

Institute of Nuclear Physics, Siberian Branch of the Academy of Sciences of the USSR
(Submitted 21 November 1990)
Zh. Eksp. Teor. Fiz. **99**, 1077–1081 (April 1991)

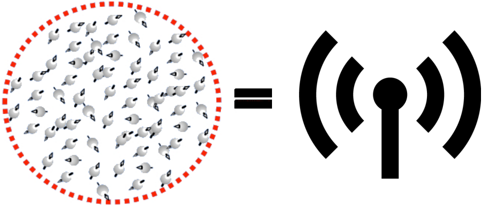
Antiferromagnets with easy-plane anisotropy are proposed as axion detectors. It is shown that the response of the detector is proportional to the ratio of the Dzyaloshinskiĭ field to the external magnetic field; this makes it possible to strengthen the bounds on the axion-electron interaction constant.

Third paper: 1991 by A.I. Kakhizde, I.V. Kolokolov.

Interaction with matter

Axions interacts with ordinary matter :

- Interaction with photons (Primakoff and inverse Primakoff effects)
- Interaction with electronic spin (only DFSZ)



L.M. Krauss, J. Moody, F. Wilczek, D.E. Morris, *Spin coupled axion detections* (1985)
R. Barbieri, M. Cerdonio, G. Fiorentini, S. Vitale, Phys. Lett. B 226, 357 (1989)
A.I. Kakhizde, I.V. Kolokolov, Sov. Phys, JETP 72 598 (1991)

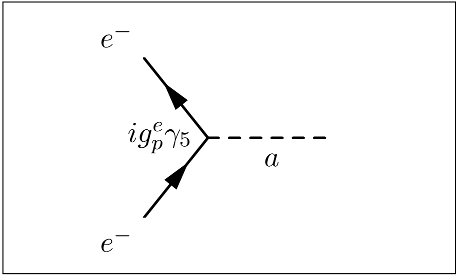
The interaction can change the magnetization in a magnetized sample.

↓

It can be treated as an effective magnetic field.

Axion-fermion interaction is described by

$$\mathcal{L} = \bar{\psi}(x)(i\hbar\partial\!\!\!/ - mc)\psi(x) - i g_p a(x)\bar{\psi}(x)\gamma_5\psi(x)$$



Using non-relativistic Euler-Lagrange

$$i\hbar\partial_t\varphi = \left[-\frac{\hbar^2}{2m}\nabla^2 - \frac{g_p\hbar}{2m}\boldsymbol{\sigma}\cdot\boldsymbol{\nabla}a\right]\varphi,$$

where the interaction term is

$$-\frac{g_p\hbar}{2m}\boldsymbol{\sigma}\cdot\boldsymbol{\nabla}a \equiv -2\frac{\hbar e}{2m}\boldsymbol{\sigma}\cdot\left(\frac{g_p}{2e}\right)\boldsymbol{\nabla}a$$

$\frac{\hbar e}{2m} = \mu_B$ is Bohr's magneton, describing the behavior of the spin.

$B_a = \frac{g_p}{2e}\boldsymbol{\nabla}a$ is the axion effective magnetic field, which acts on the sample.

$$\nabla a \neq 0 \Rightarrow \beta \neq 0$$

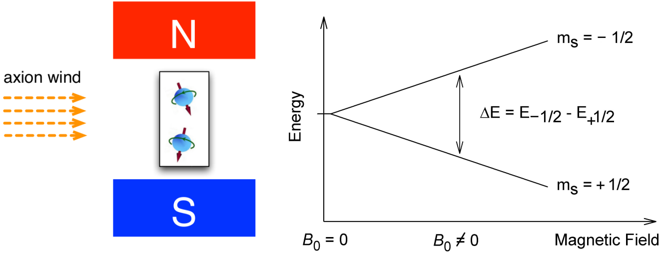
How to tune the receiver: ESR

For an axion mass of $\sim 200\,\mu\text{eV}$, $m_a c^2 = \hbar\omega \Rightarrow \omega/2\pi \sim 48\,\text{GHz}$

The effective magnetic field $B_a = \frac{g_p}{2e}\boldsymbol{\nabla} a$ is actually an RF field.

↓

The sample is tuned at a chosen ω_L with a static field B_0

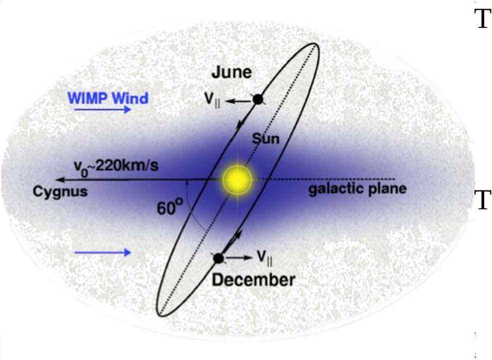


For example, $\omega_L/2\pi = 48\,\text{GHz} \Rightarrow B_0 = 1.7\,\text{T}$

$\boldsymbol{\nabla} a$
RF field
⇓
$\omega \Leftrightarrow m_a$
Mass
⇓
ESP
⇓
ω_L
Larmor
⇓
B_0
Static field

Axion background

What are the features of this $\boxed{\text{effective field } B_a}$?
An earth-based laboratory is moving in a dark matter (hp: axions) halo.



The so-called "axion wind" provides:

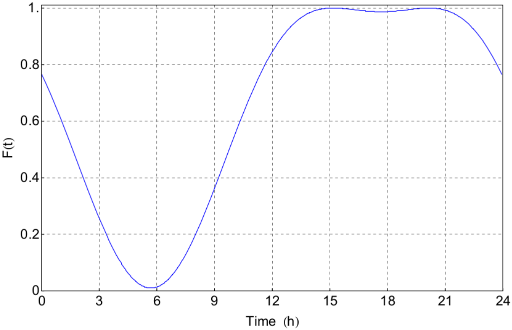
1. $\beta \simeq 10^{-3}$
2. $\lambda = \frac{\hbar}{m_a \beta c} \gg \lambda_{\text{exp}}$
3. $Q_a \simeq 2 \cdot 10^6$

That is:

1. $\nabla a \neq 0$
2. coherent axion field interaction
3. natural figure of merit

Signal signature

It also provides a signature



Daily modulation of the axion flux for the QUAX detector located at Legnaro (PD)

Different acquisitions runs during day provide different results.

$\not\Downarrow$

Measurement

$\downarrow$

Is it still not possible to make a measurement in this condition

In a free-field environment, for $f \gtrsim$GHz, radiation damping is dominated by magnetic dipole emission from magnetized the sample.

Radiation damping and microwave cavities

The axion-electron interaction is $\boxed{\text{extremely weak}}$ $g_p^e \sim 10^{-13}\,\text{GeV}^{-1}$

The signal is $\boxed{\text{anomalous oscillations of the magnetization } \boldsymbol{M}}$ $B \sim 10^{-22}\,\text{T}$

↓

The dynamics is described by Bloch's equations:

$$\frac{\mathrm{d}M_x}{\mathrm{d}t} = \gamma(\boldsymbol{M}\cdot\boldsymbol{B})_x - \frac{M_x}{\tau_2} - \frac{M_x M_z}{M_0\tau_r}$$
$$\frac{\mathrm{d}M_y}{\mathrm{d}t} = \gamma(\boldsymbol{M}\cdot\boldsymbol{B})_y - \frac{M_y}{\tau_2} - \frac{M_y M_z}{M_0\tau_r}$$
$$\frac{\mathrm{d}M_z}{\mathrm{d}t} = \gamma(\boldsymbol{M}\cdot\boldsymbol{B})_z - \frac{M_0 - M_z}{\tau_1} - \frac{M_x^2 + M_y^2}{M_0\tau_r}$$

Relaxation times:

- τ_r = radiation damping
- τ_1 = longitudinal (spin-lattice)
- τ_2 = transverse (spin-spin)

In free field the maximum allowed coherence is limited by τ_r

---

Limited phase space $\Rightarrow$ inhibition of the damping mechanism

$\Downarrow$

Sample embedded in a microwave cavity: $\tau_{\min} = \min(\tau_a, \tau_c, \tau_2)$

$$\frac{\mathrm{d}M_x}{\mathrm{d}t} = \gamma M_y B_0 - \frac{M_x}{\tau_2} - \frac{M_x}{\tau_2}$$

$$\frac{\mathrm{d}M_y}{\mathrm{d}t} = \gamma(M_z K I -) M_x B_0 - \frac{M_y}{\tau_2}$$

$$\frac{\mathrm{d}M_z}{\mathrm{d}t} = -\gamma K' I M_y - \frac{M_0 - M_z}{\tau_1}$$

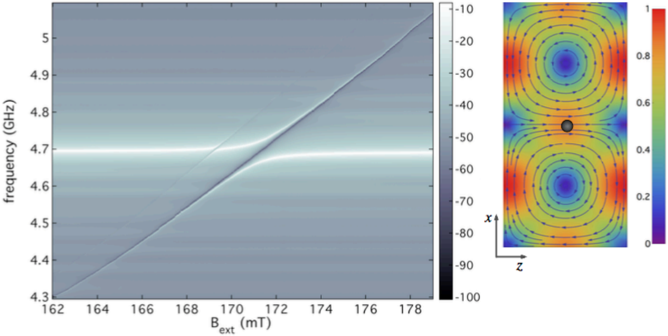
$$L\frac{\mathrm{d}I}{\mathrm{d}t} = K\frac{\mathrm{d}M_x}{\mathrm{d}t} - RI - \frac{1}{C}\int_0^t I\mathrm{d}t + V_{\mathrm{rf}}$$

New Bloch equation:

- R,L,C cavity parameters
- K and K' are geometrical coupling factors
- $I = B_1/K'$ is the equivalent current generating B_1 field

N. Bloembergen and R. V. Pound, Phys. Rev. **95**, 8 (1954)

Strong coupling regime ⇒ equations can be solved ⇒ hybridization $\omega_c \simeq \omega_L$



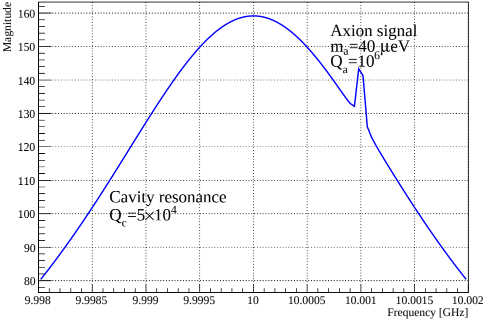
The radiation damping contributes to the frequency separation of the cavity and kittel modes.

$$S_{21}(\omega) \simeq \frac{1}{i(\omega-\omega_c) - \frac{k_c}{2} + \frac{|g_m|^2}{i(\omega-\omega_m)-k_m/2}}$$

$k_m = 1/\tau_2,\ k_c = 1/\tau_c,\ k_h = (k_c + k_m)/2$

$g_m =$ coupling strength (volume, # spins)

The signal is an excess of magnetization driven by the axion field.



ESP-cavity hybridized mode, fueled by the thermal noise.

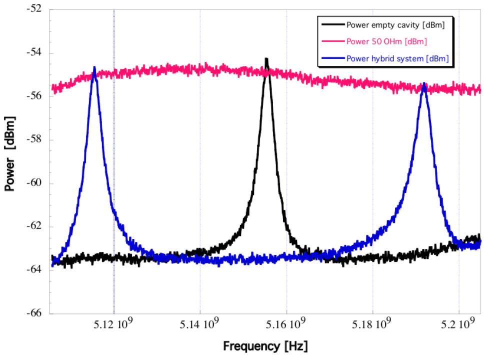
The axionic effective rf field driving the magnetization manifests as a spike in the resonance spectrum.

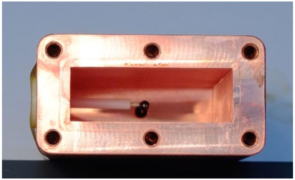
↓

A residual analysis provides a limit on the effective field B_a.

First experimental results

First measures with a YIG sphere coupled to the cavity → No excess noise





YIG properties:

- Ferrimagnet
- High spin density $n_S = 10^{28}\,\mathrm{m}^{-3}$

$\Downarrow$

Good coupling strength achieved

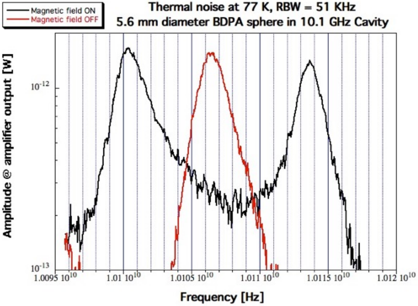
Next step: cryogenic measurements

Thermal noise spectra at lower T

Lower $T \Rightarrow$ larger YIG linewidth

WORK IN PROGRESS

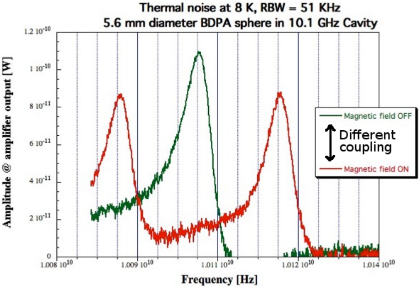
First cryogenic measures with BDPA



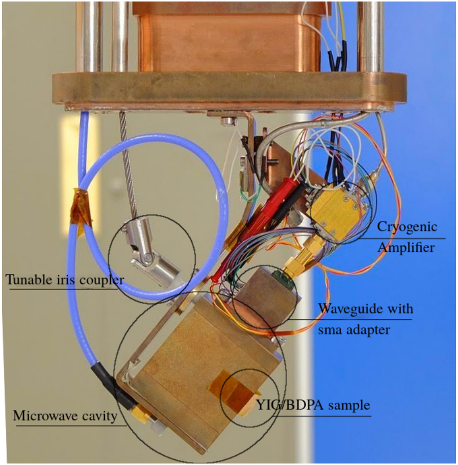
BDPA properties:

- paramagnet
- high spin density $n_S = 10^{27}\ \mathrm{m}^{-3}$

Lower coupling caused by lower spin density and sample volume.

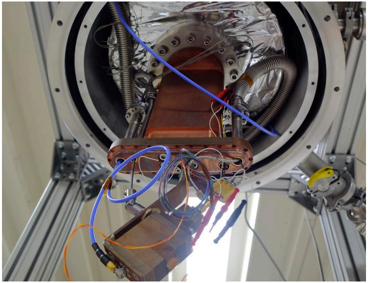


Experimental apparatus (inner parts)

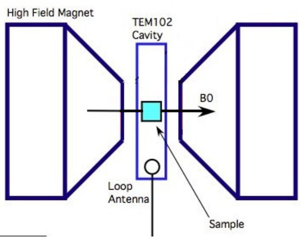


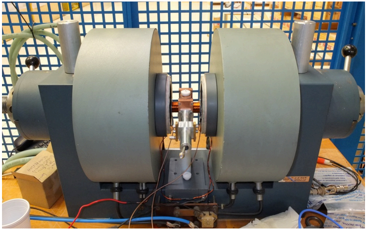
Pictures of the apparatus, with the ← different parts labelled.

Bottom view of the apparatus housed into the cryostat. ↓

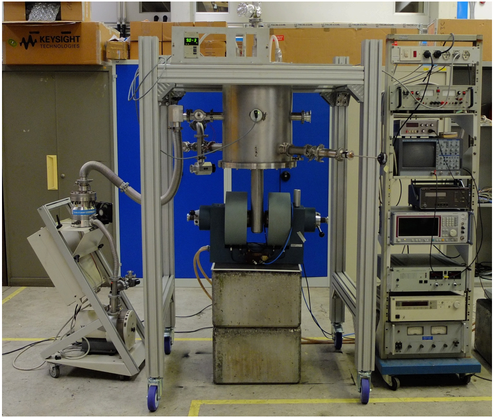


Experimental apparatus (outer parts)



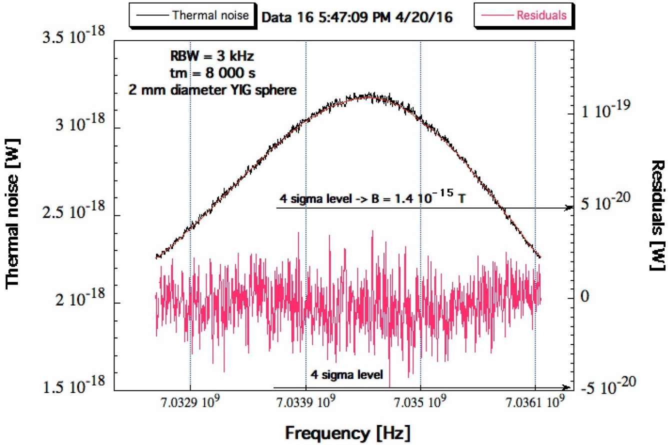


←Static magnetic field with electromagnets and full apparatus. ↓



A preliminary measurement

The axion search is performed averaging subsequent power spectra $@T_{\text{room}}$:

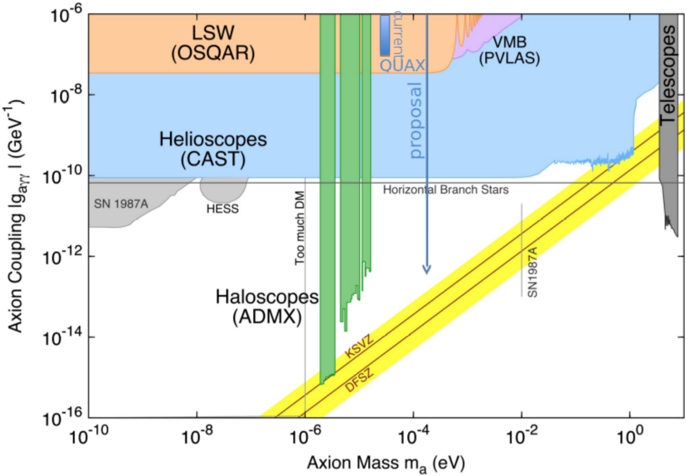


The axion signal is a sharp peak over the resonance spectra, $Q_a \simeq 2 \cdot 10^6$.

An analysis of the residuals provides the measured limit.

This measure requires magnetic field stability at the $1/Q_c$ level over the entire integration time.

Comparison in the axion-photon coupling space: previously reported measures and proposed sensitivity.



Note that the sensitivity of QUAX is limited to the electron coupling

↓

$\boxed{g_{a,ee}}$

This figure has the only purpose of make a comparison with different experiments.

Linear amplification

Axion signal peak $\Delta\omega_a/2\pi$

Detected with a RBW $= \Delta f = \Delta\omega_a/2\pi$

How far can a linear amplifier go?

$$P_{\text{min}}^{\text{thermal}} = 2k_B T\sqrt{\frac{\Delta f}{t}} \simeq 5\times 10^{-25}\,\mathrm{W}$$

$$P_{\text{min}}^{\text{SQL}} = \hbar\omega_a\sqrt{\frac{\Delta f}{t}} \simeq 5\times 10^{-24}\,\mathrm{W} \leftarrow \text{larger}$$

$T = 10\,\mathrm{mK}$, $\Delta f = 30\,\mathrm{kHz}$, $t = 10^4\,\mathrm{s}$, $\omega_a/2\pi = 30\,\mathrm{GHz}$

The Standard Quantum Limit limits the sensitivity of a linear amplification.

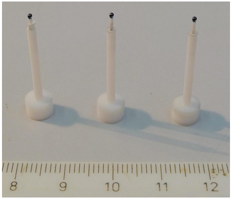
Or we can reduce the noise level...

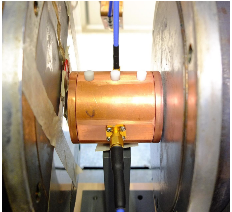
The way to the single microwave photon counter to detect spin-flip photons

Increasing the power

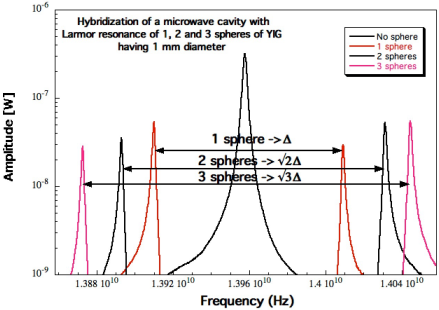
Increasing the signal rate ⇒ increasing the volume of the sample

The use of multiple YIG spheres has been tested at room temperature





14 GHz cylindrical cavity (design by David Alesini) inside a static magnetic field parallel to the cavity axis



The way to the quantum counter

The average power P_{in} absorbed by the material from the axion wind is

$$P_{\text{in}} = B_a \frac{\mathrm{d}M_a}{\mathrm{d}t} V = \gamma \mu_B n_S \omega_a B_a^2 \tau_{\text{min}} V$$

With an antenna critically coupled $P_{\text{in}}/2$ is collected as rf radiation.

$$P_{\text{out}} = \frac{P_{\text{in}}}{2} = \boxed{3.8 \times 10^{-26} \left(\frac{m_a}{200\,\mu\text{eV}}\right)\left(\frac{V}{100\,\text{cm}^3}\right)\left(\frac{n_S}{2 \cdot 10^{28}/\text{m}^3}\right)\left(\frac{\tau_{\text{min}}}{2\,\mu\text{s}}\right)\text{W}}$$

That is a $\boxed{\text{single 48 GHz photon}}$, emitted with a rate $\boxed{R_a = 10^{-3}\,\text{Hz}}$.

Note: switching to TE110 or TE120 mode of a rectangular cavity, the QUAX apparatus can detect Primakoff or spin flip photons, distinguishing DFSZ and KSVZ axions.

Conclusions

Features searched in a SMPD:

- Possibility of performing real-time measurements
- Very low dark count (~ 0.1 Hz)

Currently working on:

- Study of the materials

  behaviour of materials (YIG, BDPA and other paramagnets) at low temperatures.
- Cavity in a magnetic field

  design of a high-Q ($\sim 10^5$) cavity with a geometry useful to maximize the signal.
- External field

  realization of a highly uniform magnetic field (up to 10ppm for a 2 T field).

The R&D phase of the project is approved and will last 2-3 more years. If the goals are reached the building of the final apparatus will start.

Reference and collaboration

Details of the experiment are described in:
R. Barbieri et al, “*Searching for galactic axions through magnetized media: the QUAX proposal*” http://arxiv.org/abs/1606.02201

This is a collaboration between Laboratori Nazionali di Legnaro, University of Padova, Laboratori Nazionali di Frascati, University of Salerno and University of Birmingham.

Thank you for your time.